

# Variable El Niño-Southern Oscillation influence on biofacies dynamics of Eastern Pacific shallow water carbonate systems

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## **ABSTRACT**

El Niño Southern Oscillation (ENSO) is a periodical climatic and oceanic event caused by anomalies in sea surface temperature and nutrients over the eastern tropical Pacific (ETP). Recurring ENSO events have a significant impact on climate and the ecosystems of the Circum Pacific region. In the marine realm, ENSO is known for altering temperature and nutrient patterns, affecting the pelagic food chain and causing widespread bleaching of corals due to temperature stress. The potential impacts of ENSO on shallow benthic ecosystems as a whole, however, are poorly understood. Here we compare biogenic sedimentary facies of ETP shallow water carbonate systems in a strongly ENSO-influenced area (Galápagos Islands, Ecuador) with similar systems in an

area marginally influenced by ENSO events (Gulf of California, Mexico). Throughout both study regions, carbonate assemblages range from coral-algal dominated (photozoan) to molluscan-dominated (heterozoan). Linear statistical models, comparing the distribution of carbonates against prominent local oceanographic parameters, show that the minimum chlorophyll-a and the maximum sea surface temperature, which are strongly influenced by El Niño events, are dominant drivers shaping carbonate sediment facies in the Galápagos Islands. In contrast, Gulf of California carbonates have a distinct mean chlorophyll-a signature – the latter, a result of an upwelling-induced north-south nutrient gradient not significantly influenced by ENSO. Hence, carbonate biofacies in the Galápagos are primarily shaped by heat stress and nutrient depletion that is commonly associated with El Niño, whereas water column productivity—controlling light levels reaching the shallow water carbonate communities—dampens the impact of ENSO related sea surface temperature extremes on Gulf of California carbonate facies.

## **INTRODUCTION**

The structure and composition of carbonate sediments is intimately tied to the oceanographic conditions in which they develop (Hallock and Schlager, 1986; James, 1997; Westphal et al., 2010; Wilson, 2012). This relationship to oceanographic controls renders marine carbonate production potentially highly responsive to climatic and environmental fluctuations, especially those associated with ENSO. With respect to shallow marine carbonates, ENSO has been linked to widespread coral bleaching events (Glynn, 1990). ENSO impacts are particularly evident in the ETP, due to its geographic proximity to the oscillation epicenter, and because the region features areas of contrasting high and low nutrient levels and well-defined thermal gradients (Glynn and Wellington, 1983; Reijmer et al., 2012), while containing regions with the lowest aragonite saturation

states and ocean pH of any modern tropical ocean (Manzello et al., 2008). This unique oceanographic character forces carbonate-secreting organisms within the ETP to live near their physiological limits (Halfar et al., 2006). ENSO effects are well-known from the Galápagos Archipelago (GAL), an equatorial volcanic island chain in the southern ETP, which experienced widespread degradation following the 1982/83 and 1997/98 ENSO (Glynn, 1990). What resulted was post-ENSO coral recovery in non-upwelling northern reefs, and low regeneration in the southern, upwelling impacted islands (Riegl et al., 2015). Maximum ENSO sea surface temperatures have been shown to be strongly associated with coral bleaching and die-off events in the GAL, when temperatures exceed average summer conditions (average max  $\sim 25.7^{\circ}\text{C}$ ; annual min max variability  $\sim 4.2^{\circ}\text{C}$ ) by  $2\text{-}4^{\circ}\text{C}$  (bleaching threshold of  $28^{\circ}\text{C}$ ) for more than 8-10 weeks (Podesta and Glynn, 1997). Additionally, the southern GAL represents a unique example because it stands as the only known case where total degradation of coral framework resulted following coral mortality (Manzello et al., 2014). These findings run contrary to those for the Gulf of California (GOC), where coral loss post-1997/98 ENSO was minimal (Reyes-Bonilla et al., 2002), despite max summer temperatures of  $28.5^{\circ}\text{C}$  (min max variability of  $8^{\circ}\text{C}$ ; Cabo Pulmo; Carriquiry and Villaescusa, 2010) being exceeded by  $4^{\circ}\text{C}$  during ENSO (Reyes-Bonilla et al. 2002).

While the specific oceanographic -carbonate interactions in the GAL and GOC are complex (Halfar et al., 2006; Reymond et al., 2016), continued climate change has the potential to strengthen El Niño (Latif et al., 2015), which could enhance ENSO-related signatures on shallow water ETP carbonate factories. Here, we use exploratory analyses

and statistical models to compare biogenic constituents from GAL and GOC shallow water carbonate environments in relation to dominant oceanographic controls.

## **METHODOLOGY**

Sand-sized (63 $\mu$ m-2mm) biogenic constituents were point counted (>300 points) from SCUBA and Van Veen grab samples collected between 1 and 40m water depth off 7 islands throughout the GAL (128 samples) and 4 sites spanning the N-S extent of the western margin of the GOC (115 samples) (Halfar et al. 2006) (Fig. 1). Oceanographic data, including chlorophyll a (Chl-a, a proxy for nutrients), sea surface temperature (SST), sea surface salinity (SSS) and pH, were obtained from various sources (see GSA Data Repository (DR) for details), and the overall mean, mean anomaly, minimum (Min), and maximum (Max) values were calculated for each site. Agglomerative hierarchical cluster analyses (Euclidian distance, Ward linkage) were conducted on the unmodified raw point count data for GAL and GOC using R. A univariate linear regression tree analysis (Zuur et al., 2010) was performed for the response (binned result of the cluster analyses of biogenic constituents) and explanatory (oceanographic controls and sample depths) variables. Additional linear models were run to isolate the most dominant biogenic drivers of the cluster splits. For detailed statistical treatment see DR.

## **RESULTS**

### **ENSO-Driven Oceanographic Variability**

*Galápagos Archipelago:* Oceanographic results reveal high oligotrophic to low mesotrophic conditions at Darwin Island (GAL-North; average: 0.21mg/m<sup>3</sup>), moderate mesotrophic conditions at the islands of Baltra, Santa Fé, San Cristóbal, Española, and Floreana (GAL-SE; average: 0.30 – 0.49 mg/m<sup>3</sup>), and eutrophic conditions at Isabela (GAL-SW), caused by Equatorial Undercurrent (EUC) upwelling (average: 2.02 mg/m<sup>3</sup>;

Figs. 1 and 2; Table DR1 in the DR). Aside from the northern and western-most islands, the GAL settings fall within the coral reef turn-on/turn-off zone (CRTTZ), demarcating the Chl-a maximum ( $\sim 0.3 \text{ mg/m}^3 \text{ chl-a}$ ) for true reef development (Hallock, 2001; Fig. 2A). The slowing of upwelling during recurring ENSO events cause Chl-a levels throughout the GAL to decline sharply and give way to lower mesotrophic conditions (Fig. 1B), while temperatures in this warm-temperate (GAL-South) to tropical (GAL-North) setting can increase by up to  $8 \text{ }^\circ\text{C}$  (Figs. 1A and 1B; Fig. 2).

The average SSS of 34 Practical Salinity Units (PSU) is slightly elevated during ENSO events (mean anomaly  $\sim 0.4 \text{ PSU}$ ). Ocean pH fluctuates by  $\sim 0.09 \text{ pH}$  units (total scale) from 2003 (La Niña, average 7.88) to 2009 (El Niño, average 7.97) (overall mean  $\sim 7.9$ ) (Table DR1; Manzello, 2010).

*Gulf of California:* The GOC is characterized by a gradual increase in average Chl-a values, representing low to moderate mesotrophic conditions in the south ( $0.5 \text{ mg/m}^3$ ) to eutrophic conditions in the north ( $2.6 \text{ mg/m}^3$ ; Figs. 1 and 2). Hence, mean Chl-a values are higher than in GAL. However, while ENSO events are manifested by a reduction in the N-S Chl-a gradient in the GOC, overall Chl-a values exhibit only a moderate decline during El Nino events (Fig. 1E). With respect to SST, the warm-temperate GOC experiences greater N-S variability than the GAL (Fig. 2E). Unlike dramatic ENSO-related temperature increases in GAL (up to  $8 \text{ }^\circ\text{C}$ ) GOC SSTs increase by no more than  $4 \text{ }^\circ\text{C}$  in El Niño years (Figs 1 and 2). GOC SSS decreases N-S from 35.8 to 35.1 PSU, reflecting high evaporation in the northern GOC basin (Halfar et al., 2006). In El Niño years, GOC pH (total scale) is highest in the southernmost Cabo Pulmo ( $8.09$ )

and lowest in the upwelled waters of Bahia de Los Angeles ( 7.97) (Table DR1; Zirino et al., 1997).

### **Biogenic Carbonate Distribution**

Following a spatial pattern of declining temperature and increasing nutrients, GAL shallow water carbonates are characterized by an increasing coralline algal and diminishing coral content from GAL-North to GAL-SE, with coral being near-absent in GAL-SW (Fig. DR1A). Similarly, the GOC carbonate biota track the prevailing latitudinal temperature and nutrient gradient by exhibiting a north-south increase in coral content, a dominance of coralline algae in its central portion, and heterotrophs (molluscs, bryozoans) in the north. High nutrient/low temperature sites are characterized by high numbers of heterotroph barnacles in both carbonate systems. While the overall distribution of carbonate biota, and its relationship to dominant oceanographic controls, are comparable between GAL and GOC, major sedimentary differences include a near absence of benthic foraminifera tests throughout the GAL (<1% avg.) compared to GOC (7% avg.). Furthermore, abundant assemblages of bryozoans characterize the northern GOC high nutrient site (Halfar et al. 2006), while bryozoans play a lesser role throughout the GAL (Fig. DR1).

Five GAL and GOC sedimentary facies can be distinguished based on Euclidean-Ward clustering (Fig. 3). GAL Group I, denotes a coral-dominated (58%) photozoan facies in GAL-North. Similarly, GAL Group II in GAL-SE shows a photozoan signature, containing a mixture of molluscs (32%), corals (31%) and coralline algae (~12%). GAL Groups III and IV represent transitional heterozoan-photozoan assemblages (defined as containing a 1% - 20% combination of zooxanthellate corals and large benthic foraminifera within a heterozoan-dominated association – Halfar et al., 2006) with

significant contributions from molluscs, coralline algae, serpulids, barnacles, and bryozoans, plus 7%–10% corals. GAL Group V represents a coralline algal-dominated group (49%). Spatially, groups III-V occupy the mid-mesotrophic peripheral islands in GAL-SE, with GAL Group III—exhibiting the highest heterozoan contribution from all GAL groups—represented most strongly in the upwelling region of Isabela (GAL-SW; Fig. 3A).

GOC Group A, in the low mesotrophic south, is a mollusc dominated (41%) photozoan group, with significant contributions from corals (26%) (Fig. 3B). In contrast, the bryozoan (46%) GOC Group B is solely found in the northern upwelling site, and represents a heterozoan assemblage. The mixed photozoan-heterozoan GOC Group C is represented in the higher latitudinal collection sites of Punta Chivato and Los Ángeles. GOC Groups D and E are distinguished by high percentages of coralline algae (34% and 56%, respectively) and predominate in the moderate to high mesotrophic sites of San José and Punta Chivato (Fig. 3B).

### **Statistical Model Results**

At GAL, following depth (~14m), which divides higher coral (shallow) from higher coralline algae contents (deeper), Max SST and Min-Chl-a are the dominant controls over the distribution of the biogenic cluster groups, (Fig. 4A), while coralline algae and corals are the most significant biogenic constituents, affecting the group divisions within the cluster analysis for the GAL (Fig. 4B). Hence, the most defining aspect of GAL biogenic constituents is the varying abundance of coralline algae and coral at different sites.. This is similar to the GOC where varying abundances of coralline algae, and coral, as well as molluscs, best group sites based on the clustered biogenic data

(Fig. 4D). At GOC, mean Chl-a was the dominant control on the carbonate systems throughout the region (Fig. 4C).

## **DISCUSSION**

Fluctuations in temperature and nutrients, as a result of seasonal and long-term upwelling processes, have a significant impact on carbonate-producing communities (Hallock and Schlager, 1986). In both the GAL and GOC, examinations of long-term averages and cluster analysis, clearly show Chl-a to control CRTTZ. A photozoan association was observed at GAL in the low mesotrophic/upper oligotrophic (<CRTTZ) sediments of GAL-North (Darwin), a transitional biogenic spectrum was associated with moderate-upwelling (inter-CRTTZ) sites in GAL-SE (Fig. 1; Fig.3A), and a heterozoan association was found in EUC upwelling-influenced waters west of Isabela (GAL-SW; >CRTTZ; Fig. 3; Fig. DR1). However, in addition to this EUC/nutrient driven sediment pattern, is a strong—but short-term— ENSO-mediated SST and Chl-a control (shown in the dominant Max SST and Min Chl-a signature in our models), which primarily influences fluctuations in coralline algae and coral (Figs. 4A and 4B). The overriding ENSO signatures in the model cannot be separated from the nutrient/CRTTZ trend we see in Fig. 2, but reveal an integral role of these periodic El Niño stressors on GAL sediment evolution.

The importance of short-pulse ENSO events on long-term sediment distribution is clearly discernible. The model results (Fig. 4), based on data from 2002-2014, represent average strength ENSO conditions, and do not signal the stronger 1982/83 and 1997/98 ENSO events, which caused a lot of the recent sedimentological changes observed in the GAL-SE. These findings could indicate a long term influence of average strength ENSO/seasonal cycles on time averaged GAL sediments, which drive the southern sites

to teeter on a biogenic fulcrum. The strong 1982/83 and 1997/98 events caused widespread heat-related coral degradation throughout the entire archipelago (Glynn, 1990), and while strong regeneration was documented at the low-nutrient Darwin Island site (Riegl et al., 2015), near-total loss of corals in the southern, mesotrophic, archipelago following the 1982/83 ENSO was followed by minimal recovery (Glynn 1990), and a subsequent shift to a coralline algae dominance of sediments (Halfar and Riegl, 2013). These findings highlight the potential for temporally significant fluctuations in shallow water carbonate budgets following environmental perturbations such as those experienced during strong ENSO or tropical cyclone events (Perry and Larcombe, 2003). Some southern GAL carbonate sediment producers like corals, which develop within higher on-average nutrient levels and lower on-average temperatures, than those at the oligotrophic Darwin site, exist near their upper threshold for oceanographic tolerance, and suffer far greater changes during the simultaneous high SST and low Chl-a anomalies of El Niño events (Glynn 1990). In addition, higher background nutrient levels, during La Niña and post-ENSO, could play a role in inhibiting coral reef recovery at these southern sites (Riegl et al., 2015). These changes tip the balance to net erosion (Perry et al., 2012), which affects sediment composition by allowing coralline algae, as well as heterozoan carbonate producers to fill the ecological void. These SST and Chl-a anomalies may ultimately be responsible for the observed lack of foraminifera in the GAL (Reymond et al., 2016), however additional research is needed.

Higher average nutrient concentrations in the GOC serve as the primary driver of carbonate distribution (Fig. 4C). While the high Chl-a levels (>CRTTZ) and low temperatures throughout GOC limit significant coral development in all but the southern

site of Cabo Pulmo, GOC maintains a facies pattern similar to that of GAL. Coralline algae exert the strongest influence on the cluster distribution, although corals are present at all sites (Halfar et al., 2006). In contrast to GAL, significant coral mortality has not been observed despite ENSO events causing an increase of SST throughout GOC up to 4°C (Reyes-Bonilla et al. 2002). These geographic disparities reveal that corals respond not only by prevailing temperatures but also by the preceding temperature regimes, including duration and rates of change (Podesta and Glynn, 1997).

## **CONCLUSIONS**

Shallow water carbonate development results from complex biological and oceanographic interactions (Wilson, 2012). The overriding importance of average nutrient and temperature regimes on determining global carbonate facies distribution (Halfar et al., 2006; Riegl et al. 2015) is supported by our Eastern Pacific data. However, the surprisingly strong influence of relatively short-term, yet significant excursions from the long-term means—due to events like ENSO—on time-averaged carbonate sediments is shown here. In the mesotrophic SE Galápagos (GAL), these carbonates are highly susceptible to long term ecological shifts with strong, short-term ENSO-related, temperature and nutrient anomalies. The higher presence of corals throughout the southern GAL prior to the 1982/83 ENSO is suggestive of the historically seesaw-like nature of these anomaly-driven phase shifts. However, with the acceleration in the frequency of strong ENSO events due to anthropogenic climate change (Cai et al., 2014), it is unlikely that recent biotic changes, observed in the southern GAL will revert in the near future.. In contrast, the apparently greater resilience of the Gulf of California (GOC) coral environments, with respect to ENSO, may indicate the potential for the southern GOC to serve as a refugium for ETP corals (Riegl, 2003).

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## FIGURE CAPTIONS

Figure 1. Maps of Chl-a and SST for GAL (A-C) and GOC (D-F). Colors represent Chl-a and dotted lines show SST isolines. (A,D): average MODIS-Aqua Chl-a and SST from Jul 2002- Nov 2014. (B,C,E,F): SeaWiFS Chl-a records (NASA-Giovanni) and NOAA Optimim Interpolation (OI) SST data. (B,E): El Niño conditions from Dec 1997- Mar 1998. (C,F): La Niña conditions from Nov 1999-Feb 2000. Map A is divided into Northern (GAL-North), Southeast (GAL-SE) and Southwest (GAL-SW) regions. Figure reveals strong SST and Chl-a anomalies experienced throughout the GAL during ENSO. ENSO date ranges selected from the Oceanic Niño Index (ONI).

Figure 2. Relative trophic categorizations of each collection site at GAL (A,B) and GOC (C,D). Black bars in A,C represent the coral reef turn on, turn off zone (CRTTZ;  $\sim 0.3\text{mg/m}^3$ ) (Hallock, 2001). Abbreviated sites: DN = Darwin, SC = San Cristóbal, IS = Isabela. \*Other Sites = Baltra, Santa Fé, Floreana, and Española, which have average Chl-a levels within CRTTZ. LA = Los Ángeles, PC = Punta Chivato, SJ = San José, CP = Cabo Pulmo.

Figure 3. Untreated Euclidean Ward cluster analyses for GAL (A) and GOC (B) divided into 5 predominant biogenic groupings (I-V for GAL and A-E for GOC) in each cluster dendrogram). Blue dotted lines show cutoff distance for each cluster analysis (200). Map pie wedges show general % representation of cluster groups at each collection site. Pies represent average percent component of each biogenic category within cluster groups. OT = other, ML = mollusk, BN = barnacle, CR = coral, CA = coralline algae, SR = serpulid, BY = bryozoan, EC = echinoderm. For detailed biogenic percentages see Figure DR2 and Table DR3.

Figure 4. Relationships between oceanographic controls and biogenic distribution of cluster analyses (Fig. 3). (A,C) Linear relationships between oceanic parameters and biogenic arrangements within the cluster analyses, showing dominant oceanographic controls on sediment distribution throughout GAL and GOC, respectively. (B,D) show the most dominant biogenic categories used to define clusters for GAL and GOC, respectively. GOC sediment distribution is governed primarily by mean Chl-a ( $\mu\text{Chl-a}$ ), GAL sediments show strong ENSO control.

<sup>1</sup>GSA Data Repository item 2015xxx, xxxxxxxx, is available online at [www.geosociety.org/pubs/ft2015.htm](http://www.geosociety.org/pubs/ft2015.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1.

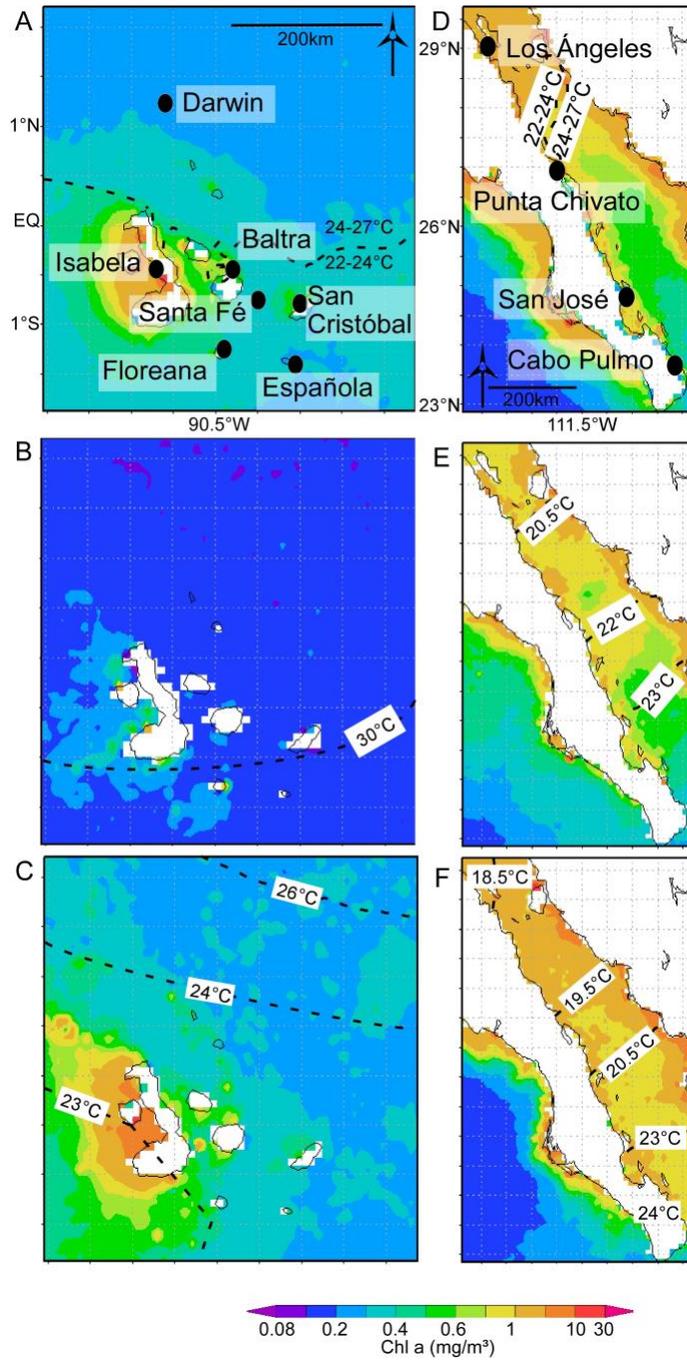


Figure 2.

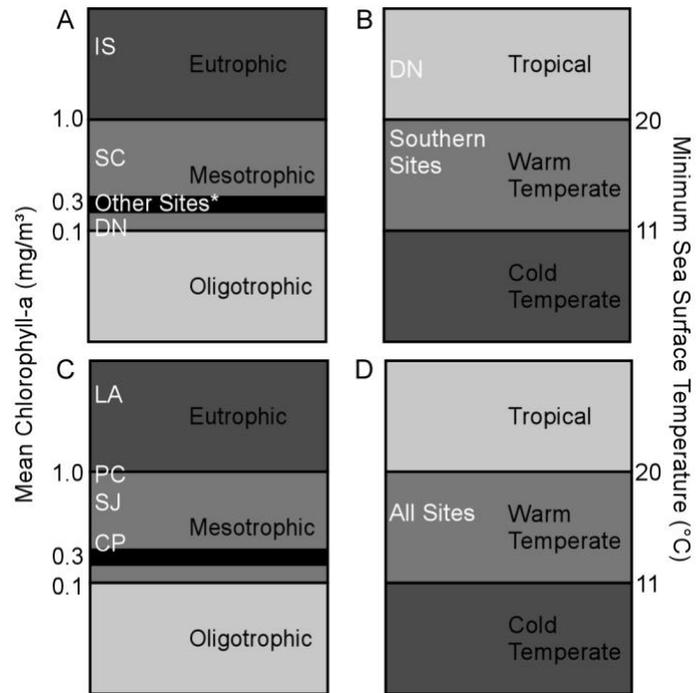


Figure 3.

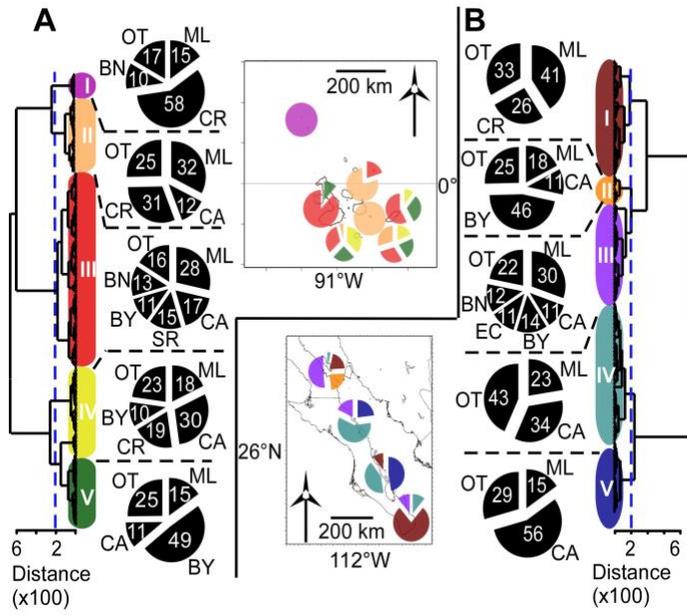


Figure 4.

